Partial suppression of multiples caused by a sequence of thin layers

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ABSTRACT

Reverberations of the source wavelet within a sequence of thin layers overshadow the signal reflected from the target area that lies below the sequence. Reverberations of the reflected signal within the sequence makes the situation even worse. We do not know which of the two phenomena is more responsible for the noisy data that we acquire in such a case. It is reasonable to assume though, that even if we could only eliminate one of those two groups of interbed reverberations our ability to image the target area would improve.

INTRODUCTION

A sequence is composed of layers as thin as 10 feet with impedances that yield reflection coefficients as large as 0.4. As the source wavelet propagates down through the sequence, interbed multiples are added to it and they are also reflected and recorded. The geological features beneath the sequence reflect a signal that contains both the source wavelet and the added multiples. Finally, more interbed multiples are added to this signal while it propagates up through the sequence and is recorded.

Recorded data from such areas show that these multiples are strong enough to overshadow both the image of the sequence and of the underlying structures.

In this paper we examine the possibility of eliminating at least some of these multiples under the following assumptions:

1. We are more interested in the geological features beneath the sequence rather than the sequence itself
2. There is some information available for the sequence (for example there exists a well in the area and we can assume the sequence composition does not change much laterally)

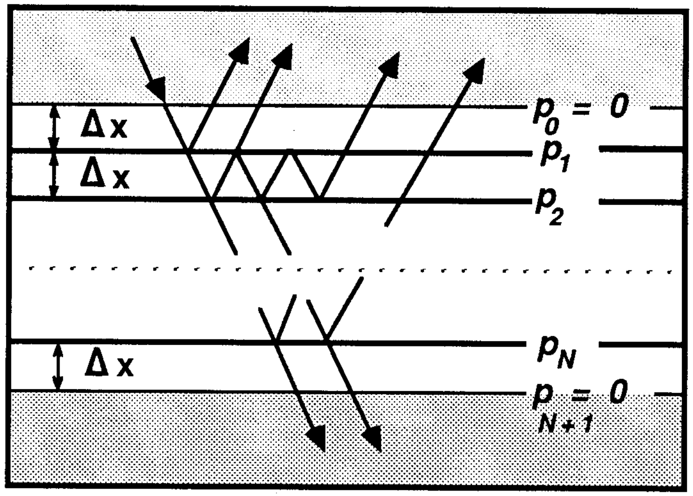

FIG. 1. Normal incidence modeling of the reflection experiment

Using the idea of the generalized wavelet we could in theory decompose our data in two parts. The first part contains the primary reflections and reverberations of the source wavelet within the sequence. This part is transmitted below the sequence. The second part of our data is the primary reflection of the first part from reflectors below the sequence and reverberations of this primary inside the sequence. If our knowledge of the sequence was good enough to allow us to model the first part of the data accurately, then we could subtract it from our data and get the second part.

The second part still contains some interbed multiples and we cannot be sure that it will be a more interpretable image of the target area below the sequence. Still, it is reasonable to hope for some improvement.

Some of the technical problems that have to be solved before one is able to apply this decomposition technique on real data, concern the goodness of the modeling: how accurate the well information is (washouts not distinguishable from fine layering?); how important is the effect of the digitization of the logs that precedes the modeling; how to estimate the scaling that needs to be done on our synthetic to make the amplitudes reasonably close to the amplitudes of our data. These problems are not solved in this paper but are the subject of further research.

In this paper we present the theoretical basis for the decomposition and some experiments on synthetic data whose main purpose is to give us an indication of whether this decomposition approach is likely to work when the technical problems are solved and thus if it is worth trying to solve them.

THE BASIS FOR THE DECOMPOSITION OF THE REFLECTION DATA

In this paragraph we will restrict our discussion in one dimension. We have N *horizontal* layers of *equal one-way travel time* Δx "sandwiched" between two halfspaces (Claerbout, 1976, Chapter 8). We are given the impedance *one-way travel-time* series ζ_i, $i = 0, \ldots, N+1$, and so the reflection coefficient series $\rho_i, i = 0, \ldots, N$, for the $N+1$ interfaces. We assume that the interfaces with the halfspaces are absorbing, that is $\rho_i = 0$ for $i = 0$ and $i > N$. A plane wave is *normally* incident to the top layer.

The initial condition is that both the pressure and (particle) velocity are zero at $t = 0^-$. The boundary conditions are that the downgoing wave at the first interface (at one-way travel-time $x = 0$) is a unit pulse $\delta(t)$ and the upgoing wave at the bottom interface (at one-way travel-time $x = (N+1) * \Delta x$) is zero at all times $t \geq 0$. (Reminder: At all times and at any depth, that is at any one-way travel-time $x = i * \Delta x$, the downgoing wave is the half sum of pressure and (velocity$\times$impedance) while the upcoming wave is their half difference).

We need to compute the *reflectance* time series $r(t)$, which is the upcoming wave at the first interface (at one-way travel-time $x = 0$), and the *transmittance* time series $\tau(t)$, which is the downgoing wave at the last interface (at one-way travel-time $x = (N+1) * \Delta x$).

In the Z-domain we denote the reflectance $R(Z)$ and the transmittance $T(Z)$ with capital letters. The Z-transform variable is $Z = e^{i\omega 2\Delta x}$.

The reflectance and transmittance are given by (Claerbout, 1976)

$$R(Z) = Z^N \frac{G_N(Z)}{F_N(Z)} \tag{1}$$

$$T(Z) = Z^{N/2} \frac{\prod_{k=1}^{N}(1+\rho_k)}{F_N(Z)} \tag{2}$$

where the polynomials $F(Z)$ and $G(Z)$ are given by the recursive relations

$$F_k(Z) = F_{k-1}(Z) + \rho_k Z G_{k-1}(Z) \quad k = 1, \ldots, N \tag{3}$$

$$G_k(Z) = \rho_k F_{k-1}(Z) + Z G_{k-1}(Z) \quad k = 1, \ldots, N \tag{4}$$

$$F_0(Z) = 1 \tag{5}$$

$$G_0(Z) = 0 \tag{6}$$

Alternatively, Resnick et. al., (1986) give a more enlightening form of this solution. They write

$$R(Z) = \sum_{k=1}^{N} \frac{T_{down_k}(Z)}{1+\rho_k} \rho_k \, Z^{1/2} T_{up_{k-1}}(Z) \tag{7}$$

$$T(Z) = T_{down_N}(Z) = Z^{N/2} \frac{\prod_{k=1}^{N}(1+\rho_k)}{F_N(Z)} \tag{8}$$

where

$$T_{down_k}(Z) = Z^{k/2} \frac{\prod_{m=0}^{k}(1+\rho_m)}{F_k(Z)} \quad k = 1,\ldots,N \tag{9}$$

$$T_{up_k}(Z) = Z^{k/2} \frac{\prod_{m=0}^{k}(1-\rho_m)}{F_k(Z)} \quad k = 1,\ldots,N \tag{10}$$

$$F_k(Z) = \prod_{m=1}^{k} [1 + \rho_m Z H_{m-1}(Z)] \quad k = 1,\ldots,N \tag{11}$$

$$H_k(Z) = \frac{\rho_k + Z H_{k-1}(Z)}{1 + \rho_k Z H_{k-1}(Z)} \quad k = 1,\ldots,N \tag{12}$$

$$H_0(Z) = 0 \tag{13}$$

Decomposition of the reflectance

Suppose now that we have a situation like the one in the first box of the following Figure 2, where a sequence of thin *horizontal* layers lies below a halfspace, while an isolated reflector is at some distance below the sequence and above another halfspace. (We are always talking about a normal incidence reflection experiment). The geology is known and the reflection coefficient one-way travel-time series would look somewhat like the one in Figure 3.b, except that there will be only one isolated reflector. (We have acquired the reflectivity series of Figure 3.b by sampling the velocity log A of Figure 3.a at 0.5ms).

Suppose that the last interface of the sequence corresponds to the N-th reflection coefficient, while the isolated reflector corresponds to the M-th reflection coefficient. Obviously all the coefficients between those two are zero.

Let us write the expression for the reflectance of this experiment. From equation (7) we have

$$R(Z) = \sum_{k=1}^{N} \frac{T_{down_k}(Z)}{(1+\rho_k)} \rho_k Z^{1/2} T_{up_{k-1}}(Z) + \frac{T_{down_M}(Z)}{(1+\rho_M)} \rho_M Z^{1/2} T_{up_{M-1}}(Z) \tag{14}$$

Note that the sum in equation (14) is the expression for the reflectance of the experiment that is shown in the second box of Figure 2. This earth model is like the one in the first box, but the isolated reflector is missing and (as indicated by the shading) the halfspace underneath the sequence has the composition of the medium that lies directly below the sequence in the first box. We call the reflectance of this experiment m as in the box and for its Z-transform we write

$$M(Z) = \sum_{k=1}^{N} \frac{T_{down_k}(Z)}{(1+\rho_k)} \rho_k Z^{1/2} T_{up_{k-1}}(Z) \tag{15}$$

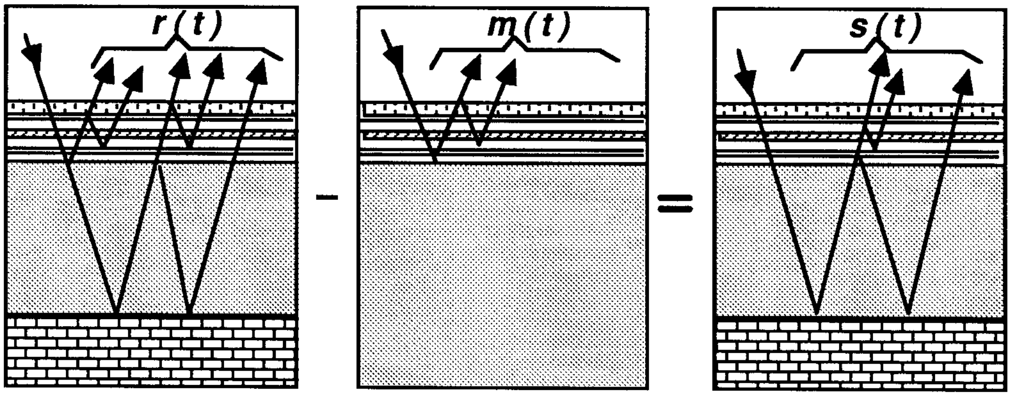

FIG. 2. Three seismic experiments. A unit pulse is incident at all three cases. $r(t)$ is the reflection response of the first experiment, $m(t)$ for the second and $s(t) = r(t) - m(t)$.

Now we can write equation (14) as

$$R(Z) = M(Z) + S(Z) \tag{16}$$

where

$$S(Z) = \frac{T_{down_M}(Z)}{(1+\rho_M)} \rho_M Z^{1/2} T_{up_{M-1}}(Z) \tag{17}$$

This is the Z-transform of the quantity that we denote s in the third box.

The generalized wavelet

If we examine equation (17) we note that its three factors have the following meaning.

$T_{down_M}(Z)/(1+\rho_M)$ accounts for everything that reaches the isolated reflector from above, including the transmitted source wavelet, the reverberations of the wavelet anywhere above the reflector and the reverberations of the reflection of the isolated reflector itself. This could be thought of as a transfer function that carries the source from the top down to the isolated reflector. This is the *generalized wavelet* incident to the reflector. From equation (9) we note that it depends on the reflection coefficient of the isolated reflector as well as all the other coefficients above it.

$Z^{1/2} T_{up_{M-1}}(z)$ accounts for all the paths from the reflector up to the top of the layers. It can be thought of as the transfer function that carries the reflection of the generalized incident by the reflector up to the top of the sequence. So it does not depend on the coefficient of the isolated reflector as we can see from equation (10).

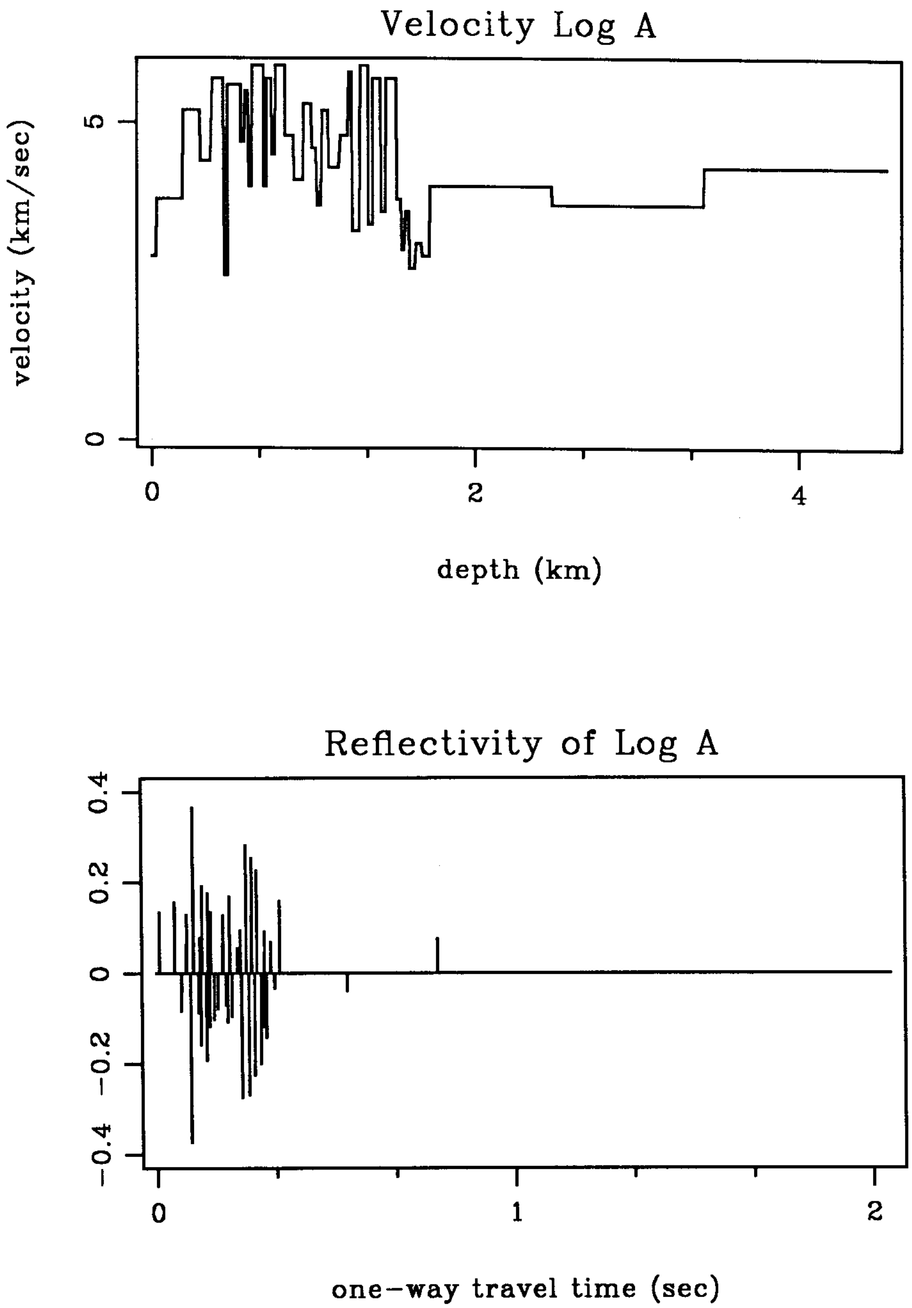

FIG. 3. Velocity log A and the corresponding reflectivity series under the assumption of constant density.

The third factor in equation (17) is the coefficient of the isolated reflector.

Which of the multiples can be eliminated?

We can see now that if we could compute an accurate model of $M(Z)$ we would be able to subtract it from our data. $M(Z)$ contains both the primary reflections of the layers in the sequence and the interbed multiples with paths confined within the sequence. This would mean that we throw away the image of the layers that is created by their primary reflections, but also we delete a part of the long tail of multiples whose image is superposed on and obscures the primary reflection of the isolated interface. We are then left with the primary reflection of the isolated reflector (which should be the first event in our remaining data) and its reverberations within the sequence.

EXPERIMENTS ON SYNTHETICS

The velocity log of Figure 3 is a digitized and simplified version of the original. The original log is from the Shell Oil Company 1-33 Yakima Minerals well in the Columbia Plateau, Washington. The upper 2km of the log show the alternating high velocity basaltic and low velocity sedimentary thin layers that are causing the severe ringing problem. The part of the log beneath 2.5km depth has been heavily edited and only two distinct velocity contrasts are left from the sedimentary layers of the original to serve as "targets" of our imaging effort. We call our edited version Log A (in Figure 3).

We assume a constant density and sample Log A at 0.5ms. The resulting reflectivity series is shown in Figure 3. Using equation (7) we compute the reflection response at the top of the first layer. This is shown in Figure 5.

We sampled Log A at a sampling interval $\Delta x = 0.5$ms. This allows a Nyquist of $0.5/\Delta x = 10^3$Hz. We compute the $R(Z)$ where $Z = \exp^{i\omega 2\Delta x} = \exp^{i2\pi f(2\Delta x)}$ for $f = 0, f_0, \ldots, 999f_0$, where $f_0 = 1000/4096$, that is on 4096 points on the unit circle.

Note that the sampling interval of the reflectance is twice the sampling interval of the log. So, the primary reflection of the, say, k-th reflection coefficient will be the k-th sample of the reflectance series but $dt = 0.5$ms for the reflectivity series (one-way travel time) and $dt = 1$ms for the reflectance series (two-way travel time).

The analogous of the second box of Figure 2 for the case of Log A is shown in Figure 4. We call it Log B and we sample it again at 0.5ms to get the reflectivity of Figure 4. The reflection response at the top of Log B is shown in Figure 6.

The analogous of the quantity $s(t)$ in the third box of Figure 1 is shown in Figure 7. It is computed by subtracting the reflection response of Log B (Figure 6) from the reflection response of Log A (Figure 5). Note that the two isolated reflections are quite visible among the multiple trains that follow them. The wave train

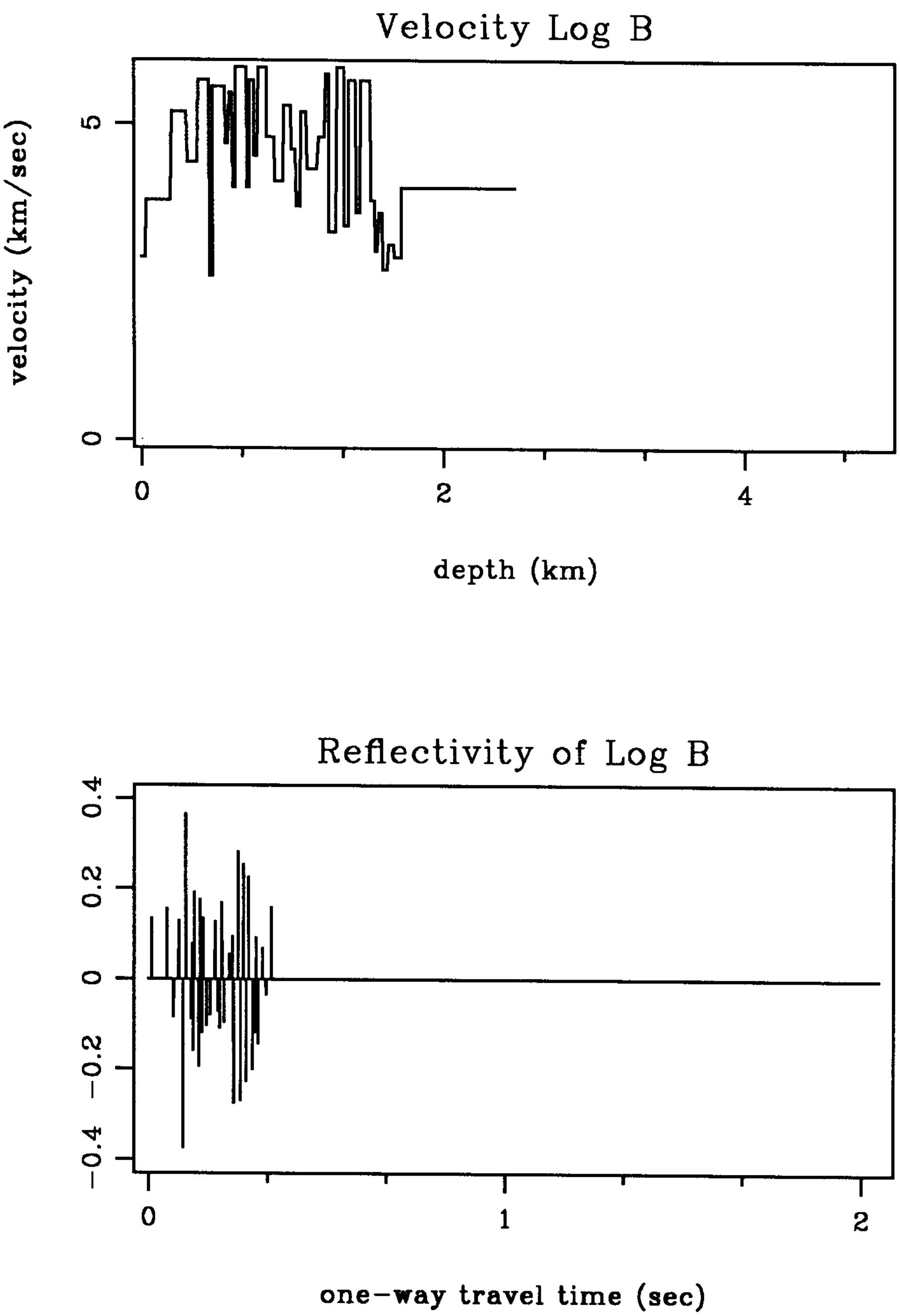

FIG. 4. Velocity log B and the corresponding reflectivity series under the assumption of constant density.

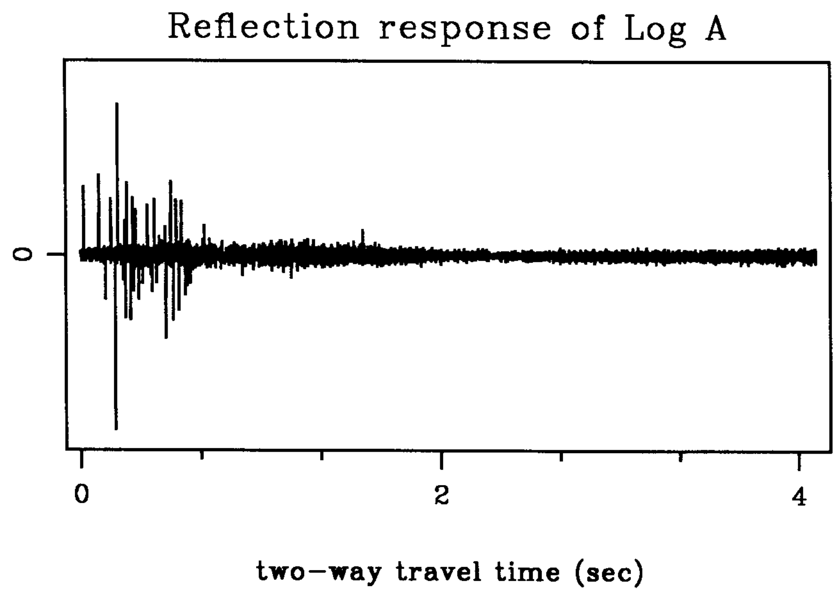

FIG. 5. The reflection response of Log A

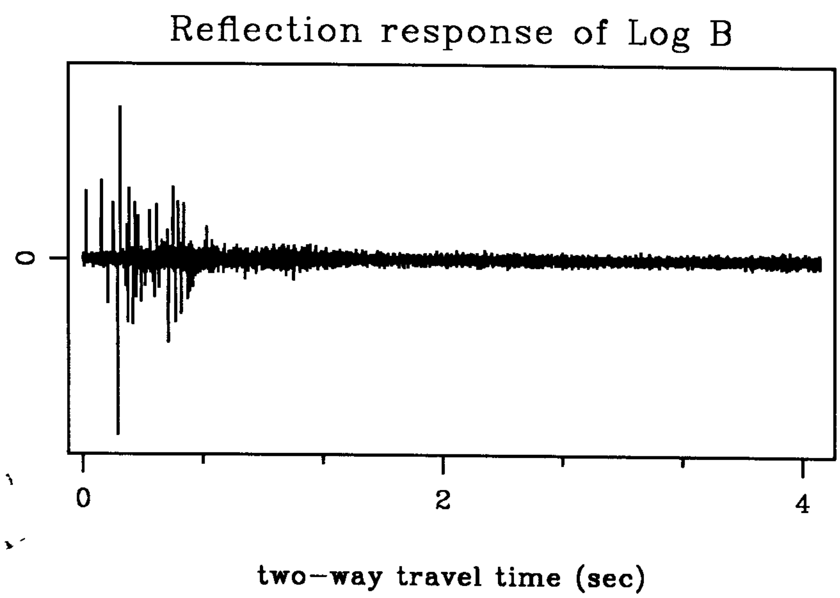

FIG. 6. The reflection response of Log B

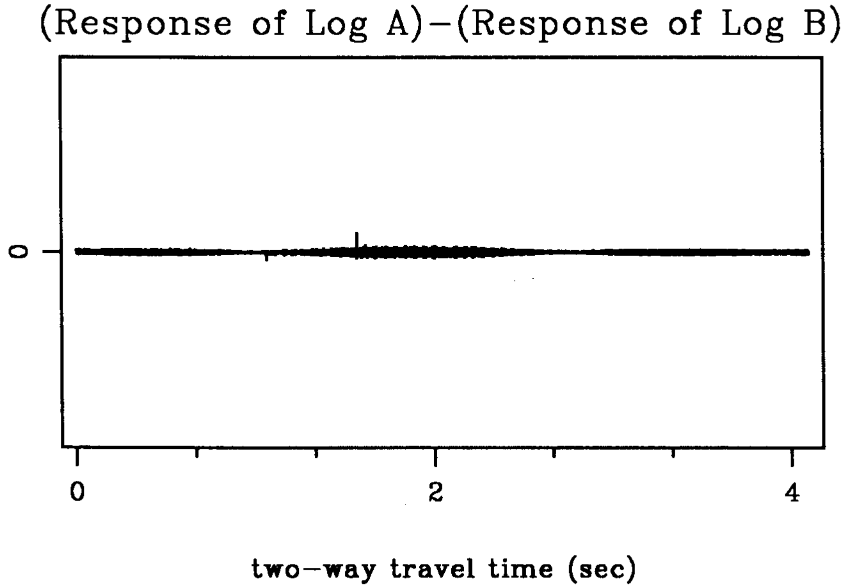

FIG. 7. The analogous of the quantity $s(t)$ of the third box of Figure 2. This is the remainder of the subtraction of the reflection response of Log B from the response of Log A.

that precedes the first reflection is an obvious aliasing problem and it is added to the multiple train that follows each reflection. Remember that the computations are done in the frequency domain and we zero padded the reflectivities of Logs A and B to get series that were twice as long. This was obviously not enough to avoid the aliasing but even so we have an indication that there can be an improvement in imaging the target reflections by the subtraction trick.

Continuing experiments with SOLID [1]

Although the analysis we have presented so far has been one dimensional, we will present now a non-zero offset modeling experiment that was done with SOLID.

Again we start from the geological model of Log A and we assume horizontal layers. This time we retain three distinct velocity contrasts from which we expect reflections at about 1 sec, 1.5 sec and 2 sec. The first layer is considered as the upper infinite medium and the last as the lower infinite medium. The point source and receiver groups are all in the top of the second layer. (So the geology differs from the one dimensional experiment where source and receiver were at the top of the first layer). The sampling interval is 0.003 sec and we do the computations for $257 \times 50 = 12800$km spread to avoid the wrap-around effects. The motion that we compute is vertical displacement.

[1] SOLID: Seismic traces for a solid layered medium, Geophysical Development Corporation.

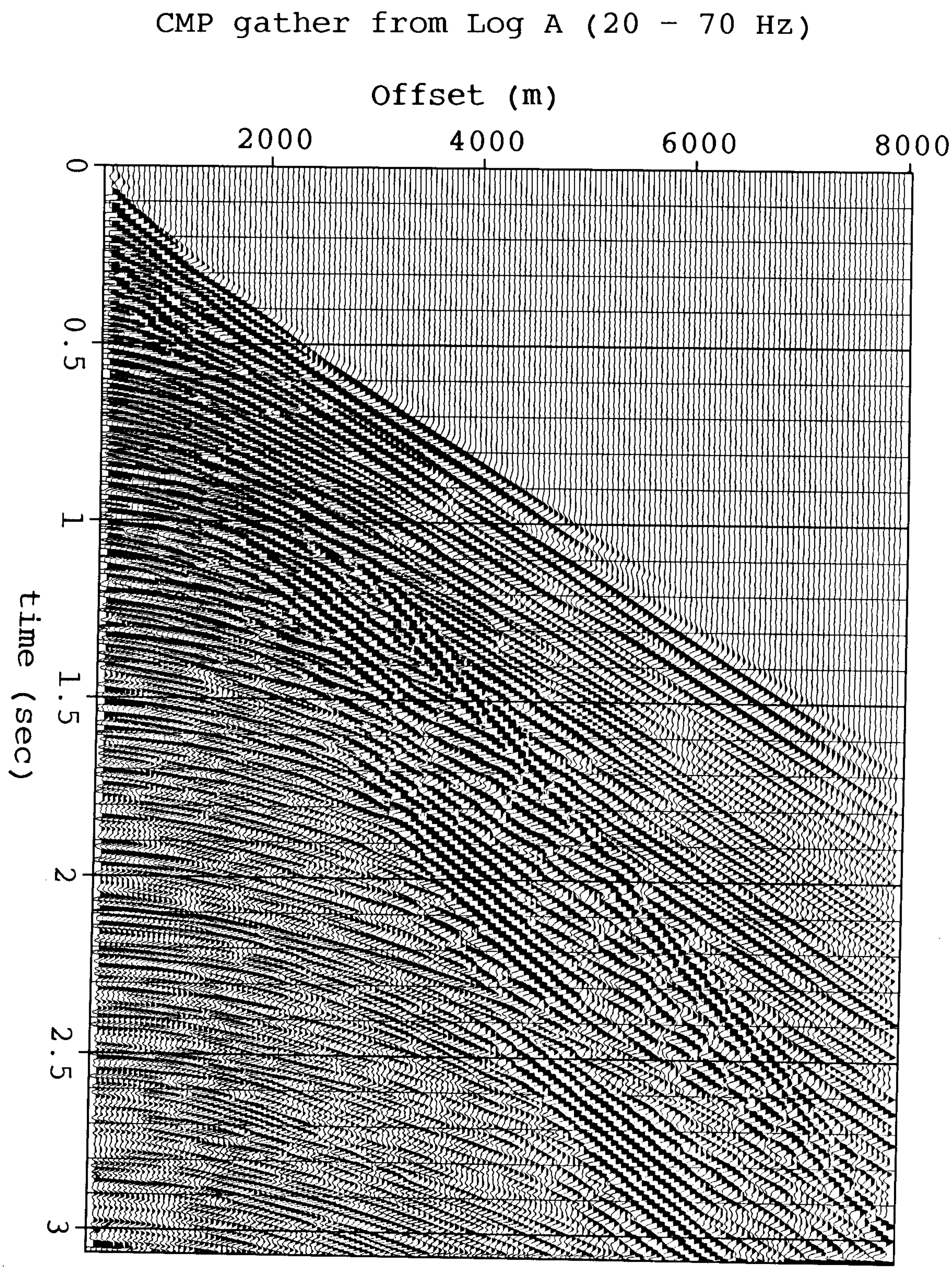

FIG. 8. Computed with SOLID, for the geology of Log A, with three "target" reflectors. Bandpassed 20 - 70 Hz and plotted with tpow=2.

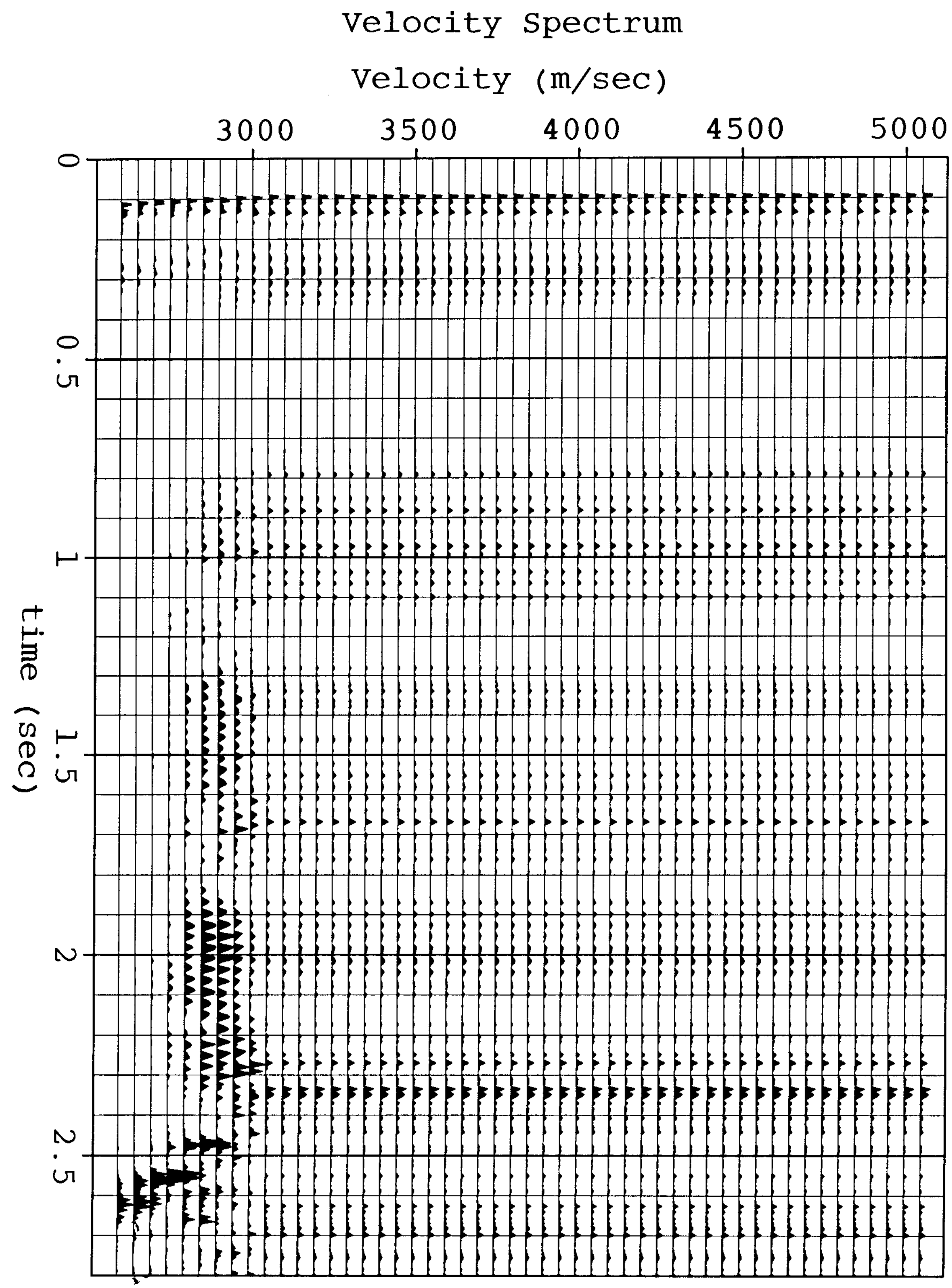

FIG. 9. The data of Figure 8 were muted above $t = x/2800$ sec. The velocity spectrum of the muted data is shown above (tpow=2).

Figure 8 is the output of SOLID with the specifications that were described above and is plotted without any gain. Although SOLID produces common shot gathers, we have labeled the data as CMP gather since we have horizontal layers and because we next do velocity analysis on these data. The velocity spectrum of the data is presented in Figure 9.

The next step of the experiment was to run SOLID for the same geology except from the three isolated reflectors. That is the input to the program is now the geology of Log B. Again we use the same parameters for the sampling interval, spread, motion computed and the same source and receiver positions.

Finally, the SOLID-made reflection data based on Log B are subtracted from the reflection data based on Log A and the result, which we call the *remainder* of the subtraction, is shown in Figure 10.

The following Figures 11, 12, and 13 show the *remainder* data bandpassed between 0-20 Hz, 20-40 Hz, and 40-70 Hz respectively, together with their velocity spectra. Note how the three isolated reflections can be seen each followed by its tail of interbed multiples that it acquired on its way up (especially on the 40-70 Hz band). Also note how *multiples attenuate faster than primaries at wide angles.* A well known useful fact.

CONCLUSIONS

In the experiments that we did on synthetics, the elimination of some of the interbed multiples has improved our ability to image the "target" reflectors that lay below the problem-causing thin layer sequence. It remains to be seen if the technical problems that were mentioned in the introduction can be solved to permit the application of the technique to real data.

ACKNOWLEDGMENTS

I would like to thank Craig Jarchow of Stanford University for providing the Columbia Plateau velocity log and for helping with the digitization. Also, Amoco Production Company for providing data and information.

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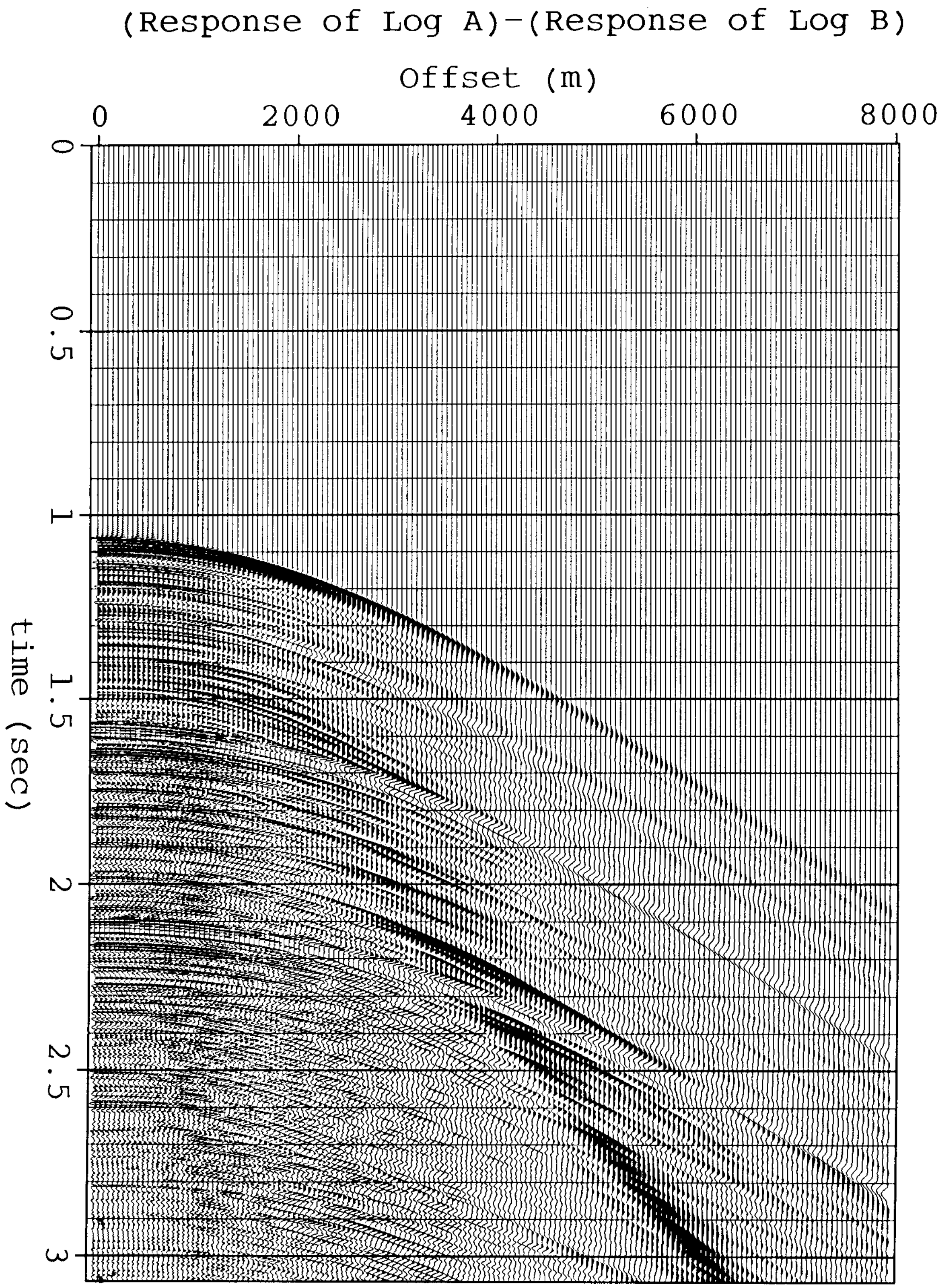

FIG. 10. The analogous of the quantity $s(t)$ of the third box of Figure 2. This is the remainder of the subtraction of reflection data computed by SOLID from Log B, from the data of Figure 8. No gain applied.

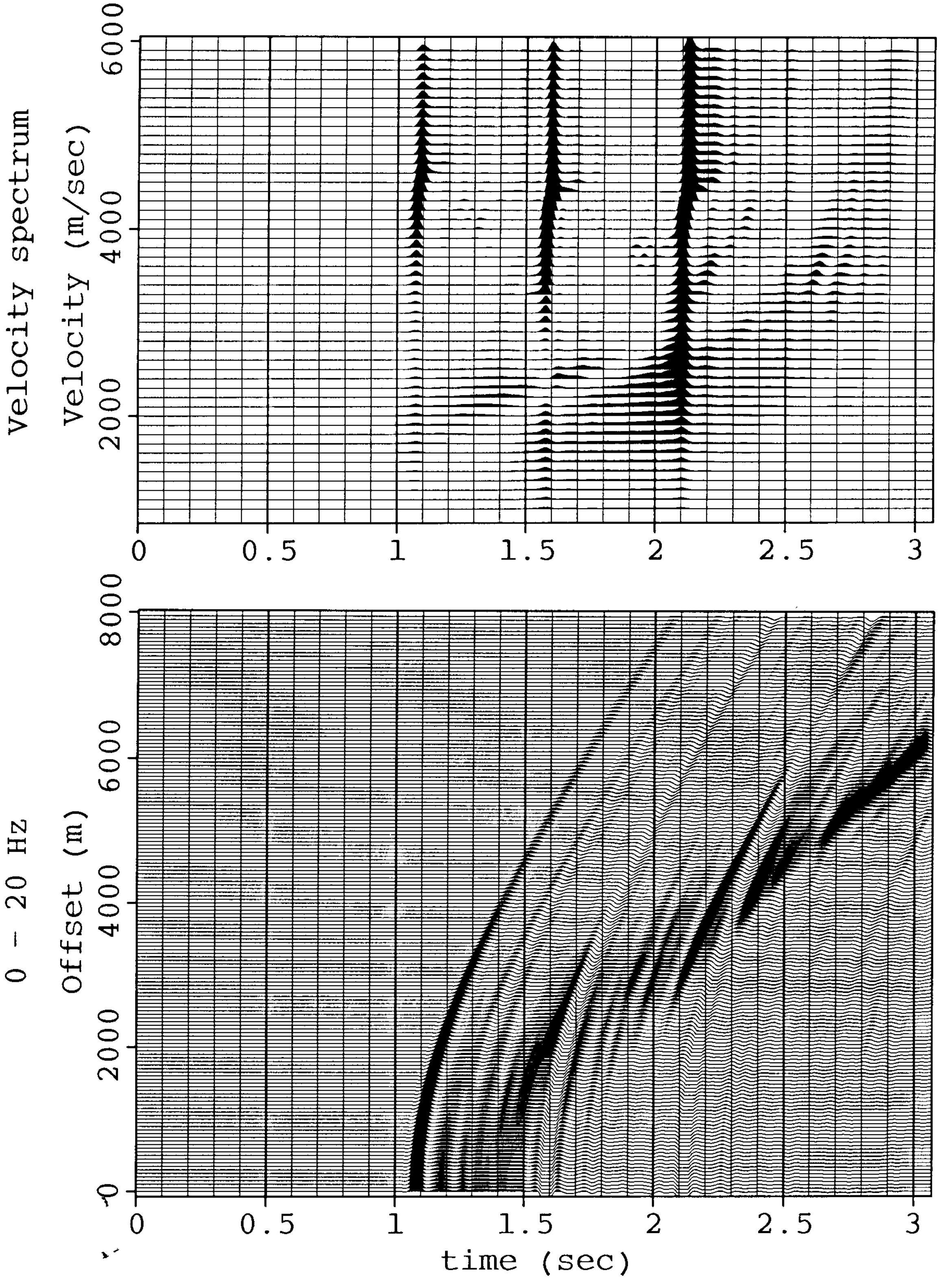

FIG. 11. The content of the data of Figure 10 (remainder of the subtraction) between 0 and 20 Hz and their velocity spectrum. No gain applied to the data.

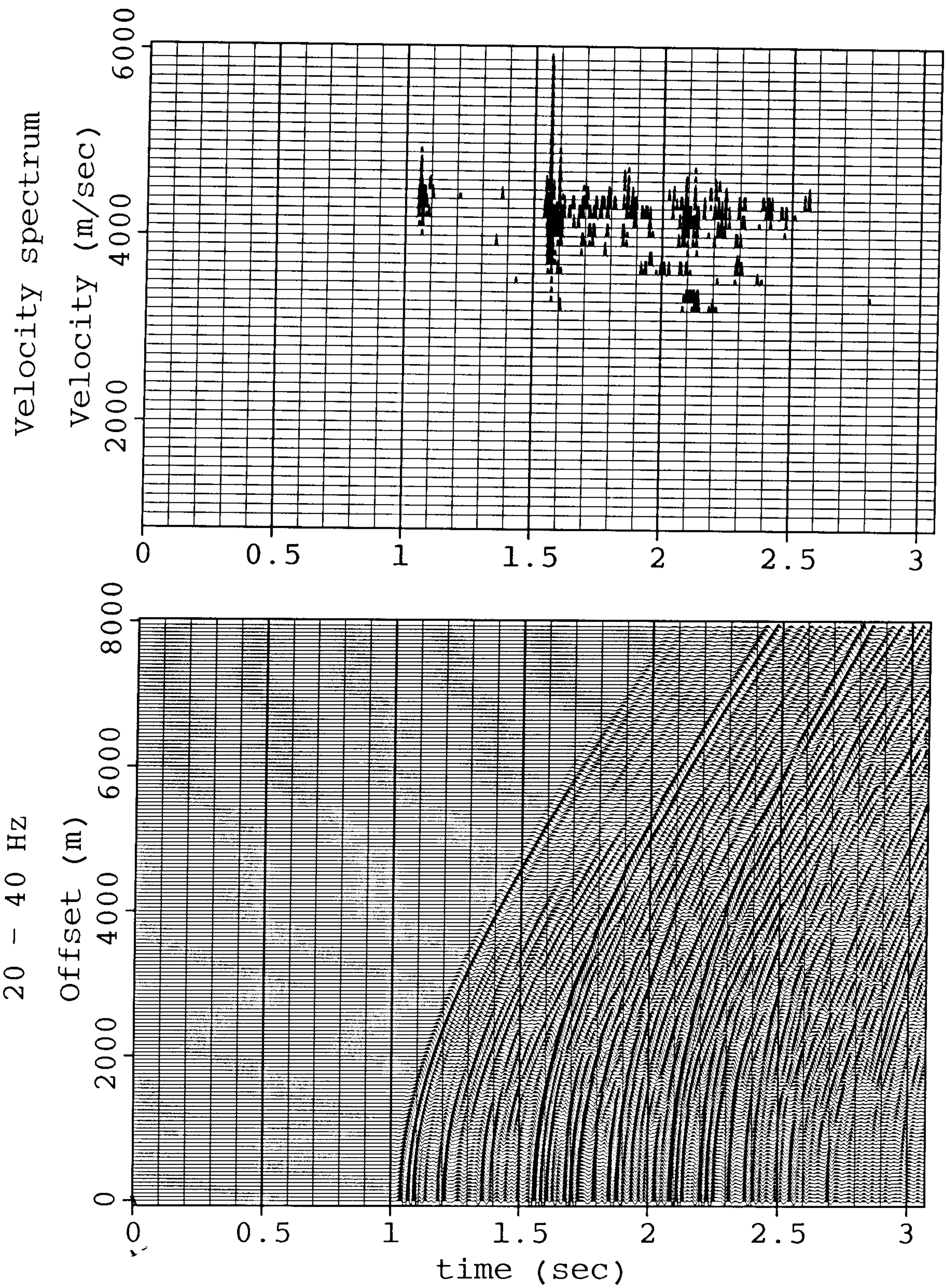

FIG. 12. The content of the data of Figure 10 (remainder of the subtraction) between 20 and 40 Hz and their velocity spectrum. No gain applied to the data.

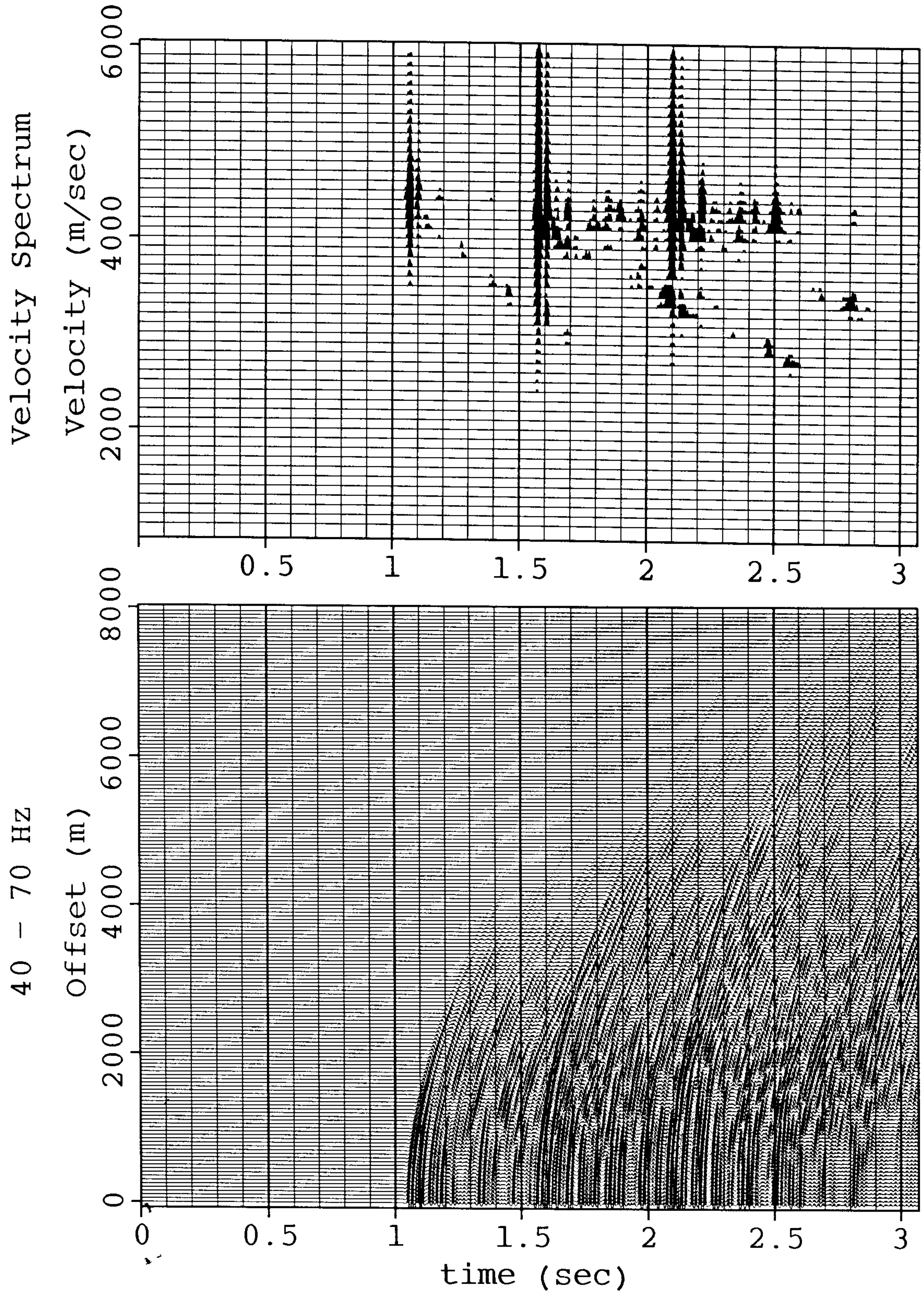

FIG. 13. The content of the data of Figure 10 (remainder of the subtraction) between 40 and 70 Hz and their velocity spectrum. The CMP gather on the left has not been gained. Note the isolated reflections at about 1 sec, 1.6 sec and 2.1 sec with their tails of interbed multiples.

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